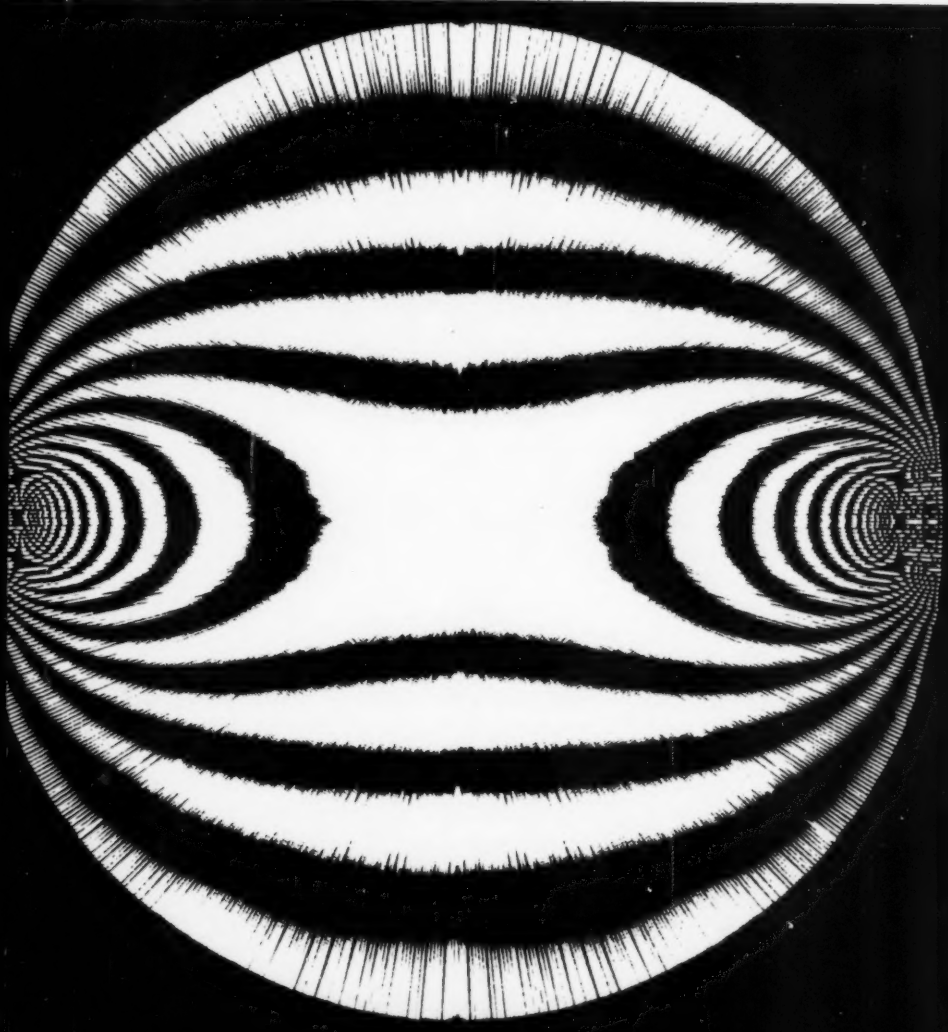
NAVAL RESEARCH

REVIEWS

OCTOBER 1970



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Portraits in Science

Dr. George Dantzig

Among Dr. George B. Dantzig's many contributions in Mathematics, his development of linear programming and the Simplex Computational Method are most acclaimed. After receiving his Ph.D. from Berkeley, Dr. Dantzig became the mathematical advisor to USAF Headquarter's and a principal member of project SCOOP (Scientific Computation of Optimum Programs). Dr. Danzig has been a research mathematician for RAND, a professor at Berkeley, and is today Professor of Operations Research and Computer Science at Stanford University. For many years Dr. Dantzig has done outstanding research at O.N.R.

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How Gas Atmospheres Produce Failure in Metals

M. R. Achter
Naval Research Laboratory

Although it has been known for almost 40 years that metals tend to fail sooner in reactive gases than in inert atmospheres, only in recent years has there been intensive investigation of environmental effects. This has largely been in response to the needs arising from two developments. One was the need for lightweight, high-strength structures for space flight. This requirement led to study of vacuum as an operating environment so that the full benefit of the inert environment, which confers vibration resistance to structural materials, would be realized. The second spur to atmosphere studies was the requirement for improved gas turbine materials for high temperature operation. Investigations such as those described here have stimulated jet engine manufacturers to work on the effect of elevated temperature gaseous atmospheres on the mechanical properties of high temperature alloys.

The Thermostructural Materials Branch of the Naval Research Laboratory has just completed a program on the effect of gaseous atmospheres on mechanical properties of metals, especially at high temperature. At the time of our entry into this field there was no knowledge of the processes controlling environmental effects and it was our objective to gain an understanding of them. Our studies have shown that important parameter is the rate of crack growth and that it could be related quantitatively to the pressure of the gas in the atmosphere.

How Metals Fail

In this discussion we are interested only in modes of failure involving a crack whose growth rate depends on the pressure of the gas atmosphere, that is, cracks which originate at the surface and grow slowly inward. Excluded, therefore, are tensile type failures which are characterized by necking and generation of an internal cavity which grows outward to a crack. An internal crack, since it is not in contact with the atmosphere, can not be affected by it. Also excluded are impact-type failures, accompanied by running cracks whose tips move at very high velocity, too high for surface saturation by gases under ordinary conditions, as will be seen later.

Here we are concerned with two types of failure, that occurring in creep-rupture and in fatigue. In creep-rupture, the specimen, under a tensile load at high temperature, elongates and grain boundary cracks grow from the surface inward. This behavior is limited to temperatures

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above approximately 1/2 T_M, where T_M is the melting temperature in degrees Kelvin. At lower temperatures tensile-type failure occurs. In fatigue, which is a very common type of failure encountered in practice, the load is applied in a cyclic manner and failure can occur at stresses considerably below those required for static loads. Since fatigue cracks always start at the surface, environmental effects operate at all temperatures.

Effects of Environment

In our early work we found that under those conditions usually experienced in most applications, the life times in both bending fatigue, Figure 1, and creep-rupture, Figure 2, were longer in vacuum than in oxygen. Typically, there is a transition range where the reduction in life is proportional to oxygen pressure and a critical point where increases of pressure have no further effect and the curve levels off. Metallographic study demonstrated that the effect of gas pressure on life time was related to its effect on crack growth rate and indicated the desirability of measurements of it for the development of a quantitative model.

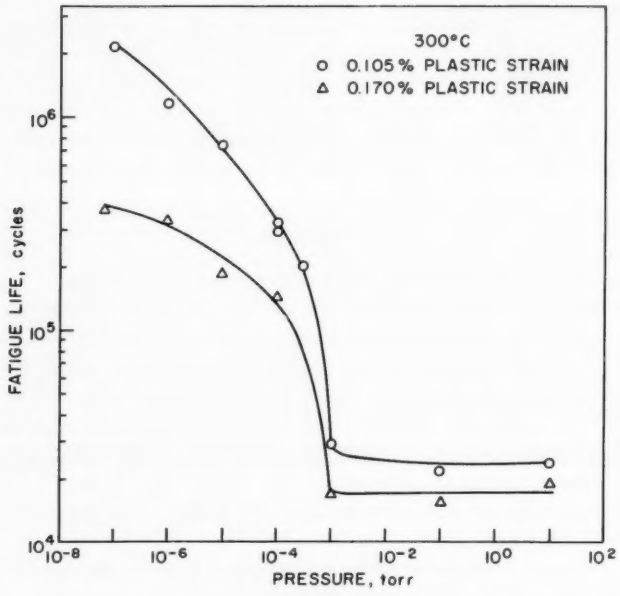

Figure 1 — Fatigue life as a function of oxygen pressure for plastic strains of 0.105 and 0.170 percent at 300°C

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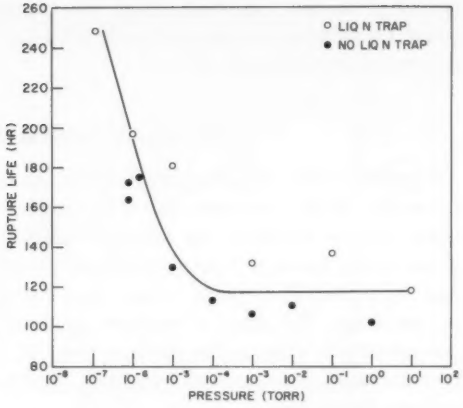

Figure 2 – Creep-rupture life of nickel as a function of oxygen pressure at 600°C and 8500 psi

To perform measurements of crack growth rate a machine, designed and constructed at NRL, vibrates the fatigue specimen in reversed bending at its resonant frequency and automatically records the decrease in it as the crack grows. A calibration curve converts frequency decrease to crack length.

In Figure 3 is an example of crack growth rate measurements as a function of oxygen pressure for Type 316 stainless steel at 5000°C. At very low pressures of oxygen the rate of growth is independent of

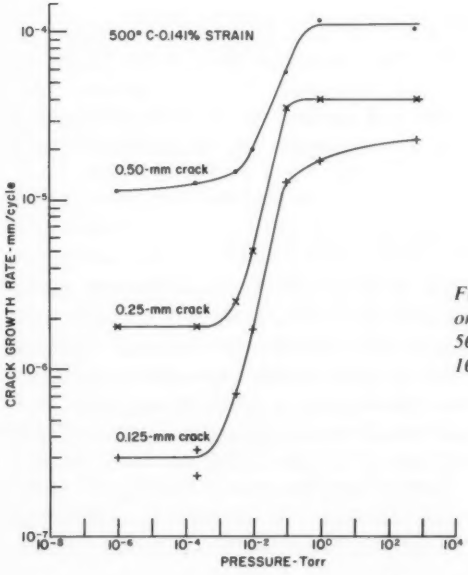

Figure 3 – Effect of oxygen pressure on rate of fatigue crack growth at 500°C and 0.141 percent strain at 10 cps

pressure. In the transition range the change in growth rate is proportional to increase in gas pressure until the critical point is reached at which the curve levels off.

The Gas Adsorption Model

Bradshaw and Wheeler first published fatigue crack growth data as a function of gas pressure and presented curves for aluminum in water vapor similar to these for stainless steel in Figure 3. To explain the shape of the curves, Achter proposed an adsorption model which states that, at the critical point where the curve levels off with increasing gas pressure, the rates of surface generation and surface coverage by gas are equal. That is, the surface must be covered in the time required for the crack tip to go from one lattice site to the next. This time interval is given simply by

$$t_o = \chi/v \text{ sec},$$

where χ is the distance between atoms and v is the crack tip velocity. Then from the kinetic theory of gases one can compute the pressure required to saturate a surface in time t_o.

This model is the first one capable of predicting the critical pressure within an order of magnitude. It has dealt successfully with the fatigue of nickel and stainless steel in oxygen, a high strength steel in oxygen and water vapor, aluminum in water vapor and air, and with the creep of nickel in oxygen.

Recently Bradshaw and Wheeler devised a critical experiment to test this gas adsorption model. They reasoned that, if the model is correct, the critical pressure should depend on crack growth rate. They consider their data in Figure 4 to show a clear proportionality between the two parameters at low pressures and to constitute good support for the model.

The Mechanism of Crack Growth

The frequency of occurrence of fatigue failure has spurred many investigations into the fundamental separation processes at crack tips. Much has been learned but much more remains to be done. There is no doubt that work on the effect of environment can contribute importantly to our knowledge of the mechanism of crack propagation. For instance, Broom and Nicholson demonstrated that it was not the oxygen in air which accelerated crack growth in aluminum but water vapor, which decomposed on the surface and generated hydrogen which, in turn, diffused into the metal. Although it is the hydrogen diffusion which does the damage, the calculation based on the adsorption model

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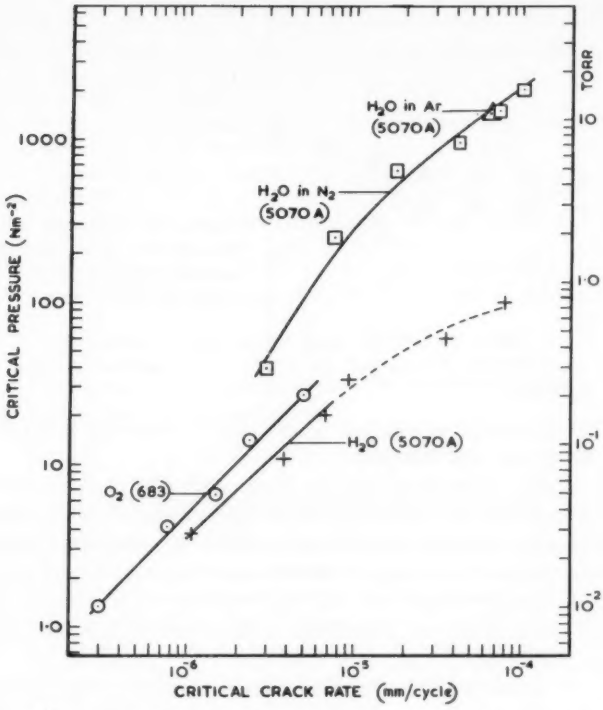

Figure 4 — Dependence of critical pressure on critical crack rate

demonstrates that the adsorption of water vapor on the surface is the rate controlling step.

For metals in which crack growth rates are increased by oxygen, as for nickel and stainless steel in Figures 1-3, there are two possible mechanisms. Figure 5 depicts, in a highly simplified manner, crack propagation as the successive breaking of bonds between atoms. If, before separation takes place, an oxygen molecule reacts with the metal pair at the crack tip, the work to break the bond is reduced. What is needed here is theoretical work to relate the reduction in bond energy to surface energy and, also needed, measurements of the work to propagate a crack in different environments. Alternatively, a number of investigators have suggested work hardening mechanisms. Coverage of the surface by an oxide layer at the crack tip, as shown for example by Smith and Shahinian, raises the work hardening rate and could, conceivably, accelerate crack propagation.

Both of these mechanisms lead to the identical calculation described above. There is promise of being able to distinguish between them by

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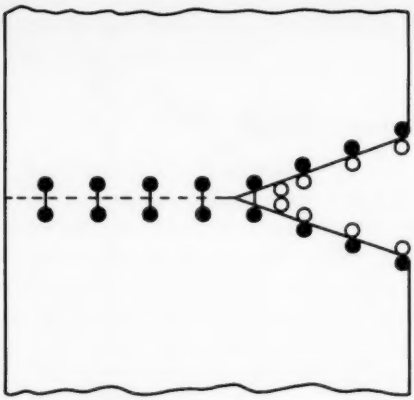

Figure 5 — Schematic of metal-gas reaction at a crack tip. Filled circles represent metal atoms; open circles represent oxygen atoms.

means of the newer techniques of electron microscopy used by Meyn and by Bradshaw and Wheeler.

A third class of mechanisms has to do with fatigue in an atmosphere of hydrogen gas as contrasted with hydrogen produced by the breakdown of water vapor. Stegman and Shahinian have demonstrated that the high strength steel curve for oxygen and for water vapor in Figure 6 conforms to the adsorption model but that the hydrogen curve does not; it is displaced three orders of magnitude from where it would be expected, based on the model.

It is not surprising that the model does not hold for hydrogen; it is well known that this gas embrittles a metal by diffusing inward and precipitating at internal interfaces and other defects and discontinuities. Therefore, a surface, adsorption model does not apply. Judging from the ability of the calculation to discriminate between rate controlling mechanisms it appears that the method could be developed into a useful tool to investigate these and related gas-metal phenomena.

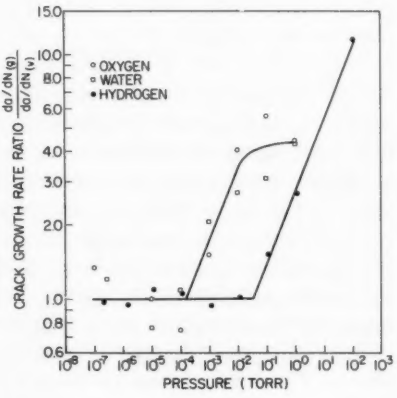

Figure 6 — Pressure dependence of fatigue crack growth rate of H-11 steel at 20°C in oxygen, water vapor and hydrogen

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A New Contribution to Systems Theory

Publication of the book "Theory of Hierarchical, Multilevel Systems," by M. D. Mesarovic, K. Macko, and Y. Takahara marks a milestone in research on the mathematical theory of systems. The material presented is the result of research on multilevel systems done at the Systems Research Center of Case Western Reserve University. The work began in 1961 and was supported by ONR. The book which was published by the Academic Press Inc., 111 Fifth Avenue, New York, New York 10003, is volume 68 in the series Mathematics in Science and Engineering.

The purpose of the book is to present a theory of large scale systems and, in fact, it is an original and unique attempt to build a mathematical theory of hierarchical, multilevel systems. The work is based on the premise that the importance of organization cannot be overemphasized and that the mathematical theory of complex organizations has not received sufficient attention. In the context of the book, a large scale system is any complex organization consisting of a family of interacting, hierarchically arranged, decision-making units. The theory is applicable to a wide range of multilevel systems, for example, networks of electrical generating plants, organizations of people and multilevel computer networks.

The book is divided into two parts. In the first part, various hierarchical systems are discussed. This provides the background necessary for formulating mathematically a specific hierarchical problem which appears to be of central importance for hierarchical systems: coordination.

In the second part, a mathematical theory of coordination is developed. A two-level system is considered with "n" decision units on the first level and a single decision unit on the second level. For example, the first level could be the program level in ONR with the second level the division level. In another example, the first level could consist of "n" computers performing individual tasks with the second level being another computer exercising central control. Coordination is defined as the decision problem of the second level unit with the objective influencing the first level to promote a goal defined for the entire system.

One of the long standing stated objectives of the mathematical sciences research program has been to develop mathematical models and techniques to provide understanding and control for large relatively complex and unstructured systems. This book is a unique contribution to that objective.

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Statistical Randomness and 1/f Noise

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Noise is the signal produced by thermal agitation or by flow of charge in solids. Satisfactory operation and high sensitivity of infrared detectors, transistors, amplifiers, and other solid state devices vital to Navy communications and detection systems depend on understanding and controlling this noise. The Office of Naval Research supports Dr. Brophy's investigation of the statistical differences between thermal agitation (Nyquist) noise and current (1/f) noise. 1/f noise is so named because the noise signal power output is inversely proportional to the frequency (f). Nyquist noise signal power is the same for all frequencies. Noise voltage of circuit elements is measured as a function of time. The pattern of a large number of these measurements is studied in terms of statistics, and the two types of noise are compared.

Nature's random statistical processes are perfect examples of the great certainty inherent in complete uncertainty. That is to say, events governed completely by chance are quite as predictable statistically as those actions that appear to be unquestionably deterministic. The resolution of this apparent paradox rests with an understanding of random fluctuations, colloquially termed "noise." Noise and fluctuations are universal in the real world, as is confirmed by the probabilistic interpretation of nature which is so successful in explaining fundamental microscopic atomic phenomena. Among other things, this means that information of physical interest is contained in noise and what is sometimes considered an annoyance can often prove to be a boon as well.

The idea that noise itself can be exploited usefully is not a new thought to those few who have studied random processes in some depth. Actually, information as diverse as the atmospheric temperature of Jupiter or the viscosity of biological fluids is obtainable directly from noise measurements. These particular examples, as well as many others like them, involve noise processes which are very much like everyone's intuitive picture of complete randomness. An often-cited example of complete randomness is the pure chance of coin-tossing wherein whether or not heads or tails will come up on the next toss is completely independent of all previous tosses. In this situation, as we will see a little more clearly in a moment, statistical properties really are quite as definite as any physical quantity. Another common everyday manifestation of noise, one having an electrical nature, is the "snow" on a television screen which becomes visible when the received signal is weak, and which exhibits a uniformly random pattern.

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The small fluctuating electrical voltage present across every electrical conductor is also an elementary noise process. A picture of the fluctuating voltage across such a conductor is illustrated in the upper part of Figure 1. The voltage (which results, incidentally, from the random motion of electrons within the solid body) is at any instant quite unrelated to that at the previous instant and does not influence the value at the next instant. Such "grass" often appears on the face of experimenters' oscilloscopes and is an interesting example of the intuitive idea of random noise.

But it is not so that all physical processes fluctuate in this rather simple manner. Quite the contrary, it begins to appear, as more information about other random processes in uncovered. An important class of processes for which the intuitive concept of randomness does not apply exactly is called "1/f noise," for reasons explained below. A

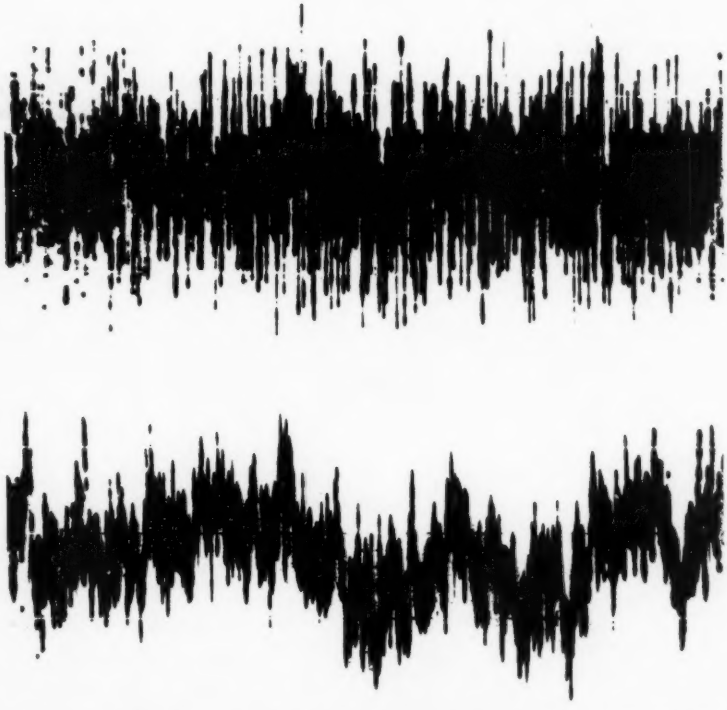

Figure 1 — Oscilloscope traces of minute fluctuating noise voltages which are observed across an electrical conductor. In the absence of electric current in the conductor the value at any instant is unrelated to values at previous times leading to a random pattern, as in the upper trace. The character of the noise in the lower trace is discernibly different when electric current is present in the same conductor.

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time record of this kind, shown in the lower part of Figure 1, is distinguishable from the previous example in that it appears somewhat "ragged." This random voltage appears across the same conductor as in the first instance except that now a steady electrical current is present in the conductor. Noise processes of this type turn out to be widespread in nature, but are only recently beginning to be understood.

It is desirable to describe randomness such as exemplified by the traces in Figure 1 in a quantitative way. Quantitative measurements not only facilitate comparison of two different noise types as the ones shown, but, perhaps even more importantly, permit interpretation of noise effects in terms of physical properties and processes. Yet, how is this measurement to be accomplished if at every instant the value of the noise is different from that of the previous instant and if any value in the future is quite unknown? A straightforward way to carry out a quantitative description is sketched in Figure 2. The random noise signal is sampled at regular intervals for a convenient duration and the voltage value at each sample instant is noted. The average value of the noise voltage is then just the sum of the individual values divided by the number of samples. This familiar, everyday idea of the average of a series of numbers provides one useful, quantitative description. Additional information is developed by calculating the difference between the average value and each individual sample, multiplying this difference by itself, summing all the products, and again dividing by the number of samples. This number represents the tendency of the individual

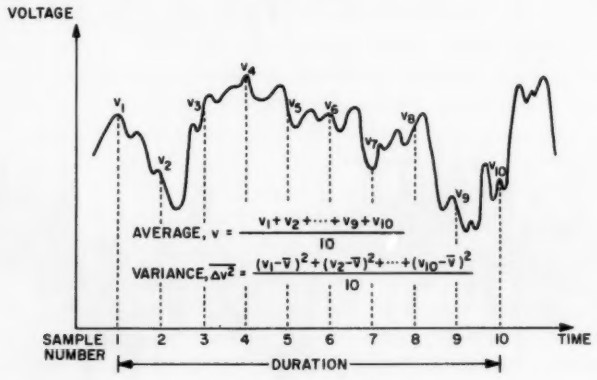

Figure 2 — A random noise is described by sampling at regular intervals for a given duration and computing the average value and the variance from the average as illustrated. Information about the speed of the fluctuations is obtained by noting the change in the calculated average and variance as the interval between successive samples is made smaller and smaller.

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samples to depart from the average value and is called the "variance." Some additional description is provided by calculating the sum of the differences each multiplied by itself three times (or four times, *etc.*), and again dividing by the number of samples. These so-called higher moments of the noise are encountered in only rather unusual circumstances since the average and the variance really describe most practical situations quite well.

How rapidly does the noise signal change from one value to another? Is, for example, the duration of the noise signals illustrated in Figure 1 equal to one second or more like one hundred years? (Actually, it happens that the duration is equal to one-fiftieth of a second in this particular example.) In principle, time effects can be examined by calculating the average and the variance for shorter and shorter time intervals between successive samples. Changes in the average and variance with the time between successive samples tell how fast the noise signal changes from one value to another, and therefore, the overall time scale which is important in the noise process.

An alternative, and much more useful technique from the experimentalist's point of view, is to describe the noise signal in terms of the frequency components it contains. Since frequency and time are reciprocally related, the two approaches are quite equivalent. Thus, the experimentalist most often measures the "spectral variance," which is just the variance as defined above except that the departures from the average are confined to a bandwidth of one cycle per second by his measuring apparatus. A plot of the spectral variance as a function of frequency is known as the noise spectrum and the area under the noise spectrum equals the total variance. Thus, the technique of measuring the noise spectrum is not only experimentally convenient but yields directly both the variance and a measure of the speed of changes in the noise signal.

Rather implicit in all of the foregoing, and quite as intuitive as the idea of randomness, is that it does not make much difference when or over what duration the averages and variances are calculated. Put another way, a coin tossed in Caesar's time is equally likely to come up heads as one thrown into the air by an astronaut. This assumption proves to be true in very many actual situations. It is technically described as "statistical stationarity," and illustrates a most significant, but often little appreciated fact: for all their apparent unpredictability, statistically stationary noise processes, that is, noise for which the average value and the variance are independent of the sample duration or the time when the average and variance are computed, are quite as firm and definite as any quantity in the physical world. In a nutshell, the variance of a statistically stationary noise is as stable as the Rock of Gibraltar. This means, among other things, that the variance of the noise at future times may be predicted quite accurately, even though

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almost nothing at all can be said about the actual instantaneous value at any instant in the future.

The spectral variance of statistically stationary noise is often independent of frequency. By analogy with white light, which is the presence of all color frequencies, such noise processes are known as white noises. The fluctuating voltage across the conductor discussed above is a classical example of this type. Since in most instances the distribution of raindrops is random, the noise of rain on a tin roof is also a white noise. If, indeed, such wide-ranging processes as coin-tossing, electrical noise, and raindrops on the roof are completely random processes, one might conclude that all physical effects have this character.

That this conclusion is incorrect has been known for sometime. There is, in fact, a variety of richness in the spectral variances of different processes. But only one other class seems to approach the universality of white noise and this one is characterized by a spectral density that is inversely proportional to frequency. This means that the spectral density becomes very large at low frequencies and is proportionally smaller at high frequencies. Because of the inverse dependence upon frequency, it is natural for this class of random process to be known as "1/f noise."

A good example of 1/f noise is the random voltage in a conductor in the presence of electric current, as mentioned earlier. An experimental noise spectrum for this case is illustrated in Figure 3. Because these measurements cover so wide a range of frequency, it is common practice to plot such data using logarithmic coordinates in which increments on both the horizontal and vertical scales increase by powers of ten. In this presentation the 1/f noise spectrum is a straight line sloping downward to the right as shown. This makes it a simple matter to distinguish 1/f noise from other processes; a white noise spectrum would, for example, be a simple horizontal line in Figure 3.

The range of frequencies covered by this data is really quite remarkable. Note that at the high frequency end, which by no means gives any indication of a limit, but has been carried only as far as the experimenter's equipment permits, the noise signal fluctuates millions of times per second. Conversely, at the low frequency end, which, similarly, appears not to be limited, the noise varies with periods lasting tens of minutes. This extreme range is one of the most intriguing features of 1/f noise. At the same time, it is both puzzling and in a certain sense annoying. The annoying aspect comes about in the following way. If the spectral variance of 1/f noise continues to increase in this fashion down to zero frequency, then the total variance (which is the area under the noise spectrum) is infinite. Now an unbounded variance suggests that individual samples tend to be very far from the average value, and what kind of nonsense is this? If individual samples tend

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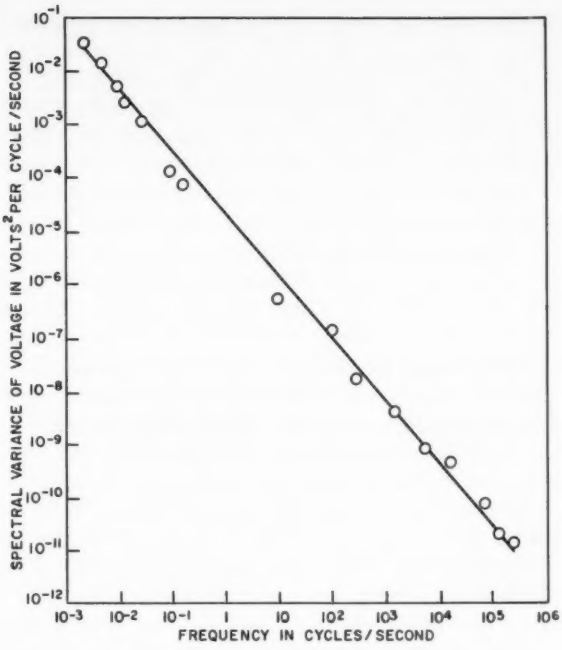

Figure 3 — The experimental noise voltage spectrum of a semiconductor diode carrying electric current. Fluctuations are seen to range from millions of times per second to longer than one cycle every 10 minutes, with no apparent limit at either the high or low frequency ends. With the ordinate and the abscissa scaled in powers of ten to accommodate the great range of values, the 1/f noise spectrum is a straight line sloping downward to the right.

to avoid their own average, can any useful measurement ever be made? And if useful measurements cannot be made, what meaning has the actual experimental data in Figure 3?

This difficulty is not really resolved by the observation that, in principle, it takes an infinite time to observe an infinite fluctuation at zero frequency. Those with orderly minds find the whole argument disturbing and conclude that the 1/f noise spectrum must flatten out at some unobservably low frequency. This approach has led to an interesting scientific game among investigators which might be termed "find the low-frequency turnover." The object of this game is to extend measurements to lower and lower frequencies in the hope of uncovering a departure from the straight line representing the reciprocal frequency trend. In spite of some rather Herculean efforts involving measurements at frequencies of the order of one cycle every ten hours, the game has

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never been won and the elusive low-frequency turnover has not been observed.

It has proved equally frustrating to explain the origin of such 1/f electrical noise phenomena. This is so not only because of the wide range of frequencies involved, but also because the noise is also quite independent of temperature. Certain rather ad hoc mechanisms can be devised which lead to a 1/f noise voltage spectrum in conductors, but these all prove to be incapable of simultaneously satisfying the experimentally certified lack of temperature dependence.

As if such affronts to the sensibilities of science are not sufficient, more recently it has been observed that the 1/f spectrum is not exclusively the province of electrical noise in conductors. Take, for example, the minute frequency fluctuations present in highly stable signals generated by quartz crystal oscillators. Quartz crystal oscillators are used as clocks by laboratories such as the National Bureau of Standards and are useful as secondary time standards because their oscillation frequencies are so stable. But the frequency of even such highly stabilized oscillators varies randomly a little bit, the variations are measurable and the fluctuations in frequency conform to a 1/f noise spectrum, as in Figure 4. While the 1/f trend is clear enough in Figure 4, there appears to be considerable scatter in the experimental results, certainly more than in the corresponding data in Figure 3. This is mainly a result of the experimental technique employed, as we will see a little later on. Of perhaps some interest is the fact that the 1/f noise spectrum extends in this data down to about one cycle per 35 days without a hint of departing from the reciprocal frequency trend.

Expanding our horizons a little further, we examine the fluctuations exhibited by long-run geological records. Seasonal temperatures during

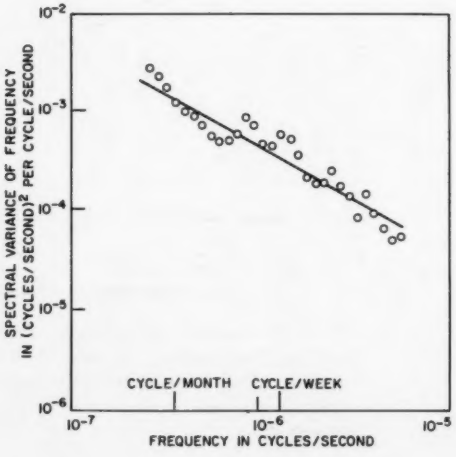

Figure 4 — The noise spectrum of frequency fluctuations in a highly stable quartz crystal oscillator is 1/f noise. Scatter in the experimental data is a result of both the experimental technique employed and the characteristics of 1/f noise.

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prehistoric times, for example, can be determined from the thickness of sedimentary layers (or "varves") found in ancient stream and lake beds. Fluctuations in the seasonal temperature over periods of many hundreds of years are available from such geologic records, and, would you believe, that the fluctuation spectrum is 1/f noise? A rather interesting example given in Figure 5 shows the seasonal temperature fluctuation spectrum at Timiskaming, Canada. Here again the apparent scatter in the data results from inherent properties of the 1/f noise process and from the experimental technique, which involves computer calculation of fluctuations from the temperature record. The lowest frequency represented in this data is approximately one cycle every 200 years.

It seems most improvident to search for a single physical process that purports to cause 1/f fluctuations in such widely diverse phenomena as those cited above, and these do not exhaust the storehouse of examples by any means. One begins to suspect, rather, that 1/f noise is a statistical phenomenon perhaps as fundamental and widespread as are white noise processes. Yet the violently different variance spectrum certainly must mean that 1/f noise processes are not completely random in the usual intuitive sense. Until very recently there has been very little experimental information to help resolve the uncertainties. Most studies

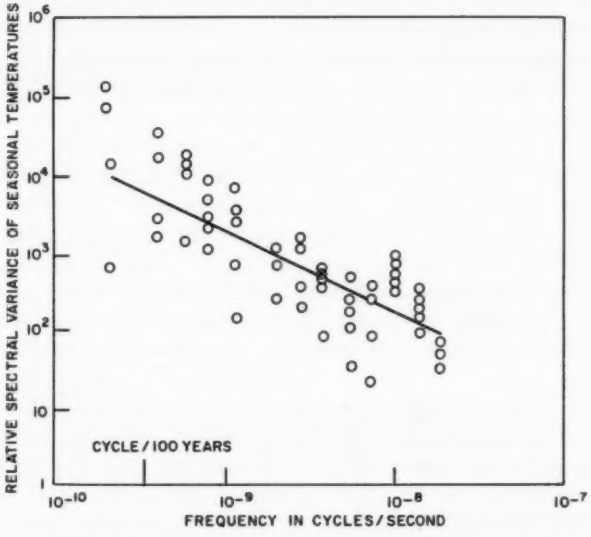

Figure 5 — Computed spectrum of seasonal temperature fluctuations at Timiskaming, Canada. The spectrum is obtained by analyzing the geological seasonal temperature record for many hundreds of years, as given by varve thickness. Varves are sedimentary deposits found in ancient stream and lake beds.

have been content to establish the 1/f spectrum or play the low frequency turnover game.

Now, however, some expanded experimental information concerning the statistical aspects of 1/f noise is becoming available. The statistics have been examined by applying a technique identical to that sketched in Figure 2 to determine average values and variances of 1/f noises. It is convenient to concentrate on voltage fluctuations in conductors because electronic sampling and measuring techniques provide multitudinous data with minimum effort. Furthermore, both 1/f noise and white noise can be studied with the same equipment, depending only upon whether or not electric current is present in the conductor under examination.

Parenthetically, it is useful for what follows to give white electrical noise in a conductor its proper name. This laudable goal is only slightly complicated by the fact that the phenomenon is known by three different names: Nyquist noise, Johnson noise, and thermal noise. Nyquist was a theorist who first derived an explanation for the phenomenon; Johnson was the experimentalist who first measured its properties; and thermal noise is apt since the magnitude of the variance depends upon the temperature of the conductor. For present purposes, the term Nyquist noise will be used. We should remember that Nyquist noise is a useful example of a completely random process, has a white spectrum, and is statistically stationary.

Elementary statistical properties of both 1/f noise and Nyquist noise can be directly explored with the apparatus sketched in Figure 6. Noise voltage signals across the conductor are amplified, sampled electronically at a regular, rapid rate and the voltage level at each sample stored in an ingenious, computer-like electronic device known as a pulse-height analyzer. With this apparatus, as many as 10,000 samples of the noise signal are taken each second and arranged according to size in the memory circuits of the analyzer. Most often, signals are sampled for a 100-second duration, which yields a total of one million samples. Such large numbers are important in fluctuation studies in order to establish properly the statistical properties of inherently random quantities.

An experimentally-determined distribution of the one-million voltage samples of 1/f noise plotted by the pulse-height analyzer after a single 100-second duration measurement is illustrated in Figure 7. The samples are distributed in the familiar bell-shaped curve known as a normal distribution. Because the shape is symmetrical, it's easy to see that the average value is just at the peak of the curve. Furthermore, the width of the curve measures the variance, since the width displays the tendency of the samples to be different from the average value. Thus, the statistical features of interest appear as if by magic from the normal distribution. It's well known that many completely random processes obey a normal

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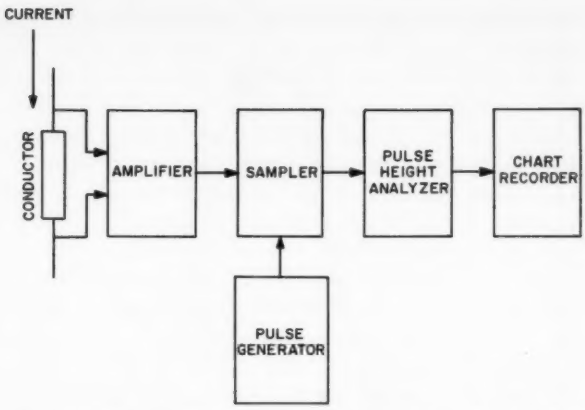

Figure 6 — Statistical properties of electrical noise signals are analyzed electronically following the technique illustrated in Figure 2 using the apparatus sketched here. Minute voltage fluctuations across the conductor are first amplified and then sampled 10,000 times per second. The sampling circuit is controlled by a pulse generator circuit which determines the sampling rate and duration. The voltage at each sample instant is measured and stored according to size by the pulse height analyzer. After a suitable duration is sampled, most often 100 seconds long, the distribution of sample sizes is plotted by the chart recorder. Both Nyquist noise signals and 1/f noise signals can be examined, depending upon whether or not current is present in the conductor

distribution. The apparatus in Figure 6 confirms directly that Nyquist noise has this property and, interestingly enough, that 1/f noise is indistinguishable on this basis.

Initial results of this kind displayed a disturbing feature: whereas normal distributions of Nyquist noise samples are essentially identical every time the experiment is repeated, this doesn't prove to be so in the case of 1/f noise. Although the samples are always normally distributed, the width of the distribution is not the same on successive trials. Some dispersion from trial to trial is common in experimental measurements and is usually attributable to minor experimental vagrancies in equipment performance. The experimentally observed variations in the variance of 1/f noise are larger than can be easily swept under this "experimental error" rug, however. It appears that the cherished statistical stationarity of variance is just not valid in the case of 1/f noise.

Indeed, collecting together measured variances of 50 different, but supposedly identical, 100-second durations of 1/f noise, as in the histogram of Figure 8, shows just how much variety is observed. The most

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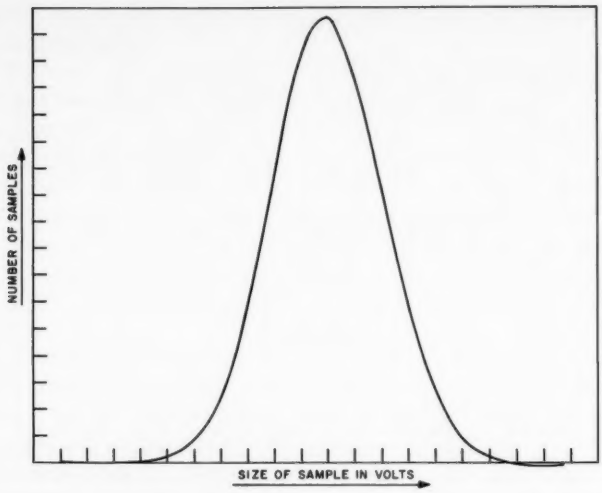

Figure 7 — Experimental chart recorder plot of the sample distribution in a 100-second duration of 1/f noise. The distribution follows the familiar bell-shaped curve which means the average sample size is at the peak of the curve and the variance is given by the width of the curve.

probable variance is the smallest value, but much larger sizes are also found. By contrast, the corresponding histogram for Nyquist noise is very much less spread out and clusters around the central peak. Minor variations in the latter case are ascribed to experimental random errors and it seems appropriate to claim that the variance of Nyquist noise is statistically stationary. The histograms in Figure 8 show clearly that quite the opposite must be true in the case of 1/f noise, and that the variance itself fluctuates. Succinctly stated, 1/f noise is a noisy noise.

The problem of how to describe such variance noise is reasonably straightforward. The variance is itself considered to be a noise and the average variance and the variance of the variance are computed using the usual definitions given earlier. It proves convenient to fashion the ratio of the average variance multiplied by itself divided by the variance of the variance. This variance noise ratio is a quantitative measure of variance noise. In the case of Nyquist noise, for example, where the variations are very small and attributed to experimental errors anyway, the variance of the variance is small and the noise ratio is correspondingly large. A value of 2000 is found for the data pertaining to Figure 8. On the other hand, the variance noise ratio for the 1/f noise data in Figure 8 is equal to 15. This means that this 1/f noise is more than 100 times noisier than Nyquist noise. Similar values have been observed for other

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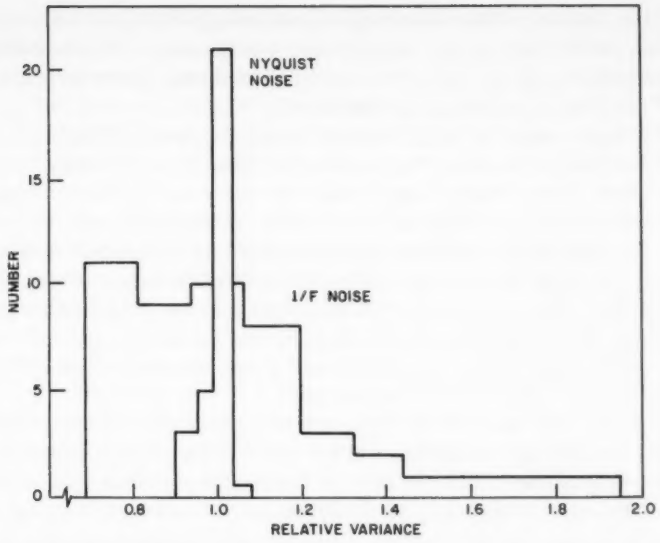

Figure 8 — Experimentally measured variances are reproducible in the case of Nyquist noise, aside from minor deviations resulting from experimental errors, whereas in the case of 1/f noise relatively large variations are found upon successive trials. Comparison of these histograms illustrates that 1/f noise is a much noisier noise than Nyquist noise. To facilitate comparison of the two noises, observed variances are related to the average value in each case.

1/f electrical noises, such as, for example, that associated with the spectrum in Figure 3.

We can easily understand now the dispersion of experimental values displayed by the experimental spectra for oscillator noise and seasonal temperature fluctuations noticed earlier. It is just that 1/f noise signals are noisier than familiar statistically stationary noises and so usual experimental techniques do not work as well. It is necessary, in fact, to obtain the average value for any statistical property of 1/f noise of interest. One of those fortunate accidents of providence decreed that the experimental techniques used in electrical noise studies automatically do this job rather well. Therefore, noise data such as those in Figure 3 are much less scattered and the 1/f trend in the spectra is easily discernible. Presumably this is one reason why for many years 1/f noise was considered to be a random electrical phenomenon only.

Notice carefully that it is extremely significant for the average variance to have some meaning. While on the one hand it is clear that 1/f noise is not statistically stationary in the usual intuitive sense and in the way experimentally verified for Nyquist noise, it must be stationary in some

XUM

less rigid fashion. Otherwise, experiments would not lead to the regularity observed in the variance histograms or to the observed reproducibility of the variance noise ratio. For want of a more descriptive term, one can say 1/f noise is conditionally stationary.

The major virtue of such a label is really to keep reminding us that intuitive ideas of randomness, such as the difficulty with infinite variance mentioned above, may not apply directly. It is conceivable, for example, that the average variance does, in fact, increase towards very large values as the duration of the observed signal lengthens while at the same time the average variance for a given finite duration has a well established value. Thus, even if 1/f noise spectra do not have an actual low frequency cutoff in the intuitive sense, they have one in the operational sense. The lowest noise frequency significant in any situation is simply determined by the duration of the experiment.

Experimental evidence for this type of behavior is shown in Figure 9 where the average variance of a 1/f noise signal is experimentally observed to increase as the duration of the observation time. These results also show scatter resulting from variance noise contrasted to the regularity displayed by the average variance values. Corresponding results

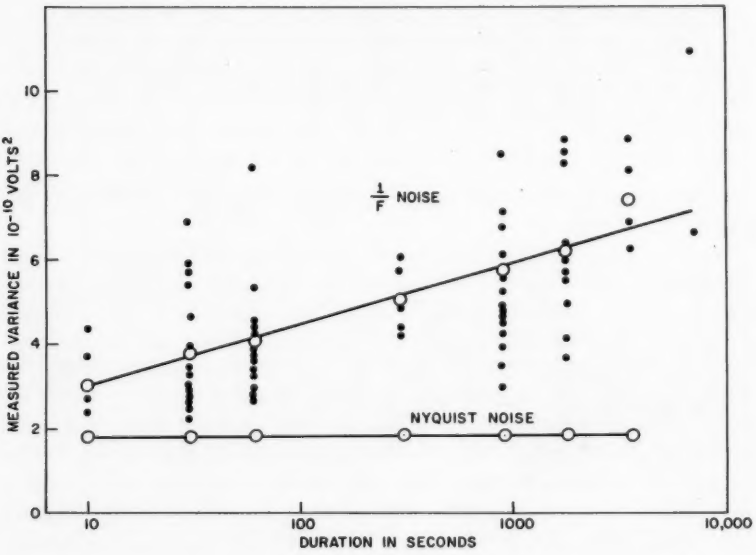

Figure 9 — The measured variance of a 1/f noise signal increases with the duration of the measurement, while the variance of statistically stable Nyquist noise is independent of duration. The data circles represent the average variance at each duration while dots indicate individual measurements. These results show that 1/f noise gets noisier as time goes by.

in the case of Nyquist noise do not show any change of variance with duration, as anticipated for a statistically stationary random process.

A very practical application of the improving understanding of 1/f noise phenomena is directly illustrated by Figure 9. In contrast to the case of Nyquist noise, measurements which are limited by 1/f noise signals cannot be improved by lengthening the observation time. Quite the contrary, in fact, since the noise variance increases with time, the longer you wait the worse off you are. This conclusion can have important consequences in designing experimental apparatus for precision measurements.

Secondly, and much less well understood, is an extension of the idea that 1/f noise is obviously not completely random. In this circumstance presumably the value at any instant depends in some statistical way on values at preceding times. Furthermore, because low frequencies are so very important in 1/f noise, the coupling between present and past extends over significantly long times. Turning this thought around, if it is possible to look back, is it not equally possible to look ahead? Then, of course, a fluctuation record of the recent past up to the present might serve to predict future values. If it seems rather ludicrous to suggest that a nonstationary noisy noise is more predictable than well-behaved completely random phenomena. Let us at least admit we have no satisfactory understanding of the statistics of 1/f noise as yet. Our appreciation of such phenomena has improved significantly recently though, giving substance to the hope that the knowledge of 1/f noise is itself not a 1/f noise process.

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28th U.S. Navy Symposium on Underwater Acoustics will be held at NRL, from 17-19 November, 1970.

41st Symposium on Shock and Vibration will be held at the Air Force Academy, Colorado Springs, Colorado, from 27-29 November, 1970.

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History of Electrically Excited CO_2 Lasers

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Boston, Massachusetts

The first electrically excited CO_2 lasers were rather long tubes containing CO_2, N_2, and helium, with the electrical discharge and the laser action taking place along the axis of the tube. The laser gas was cooled by conduction of the walls, which results in the development of relatively high gas temperatures in the center of the discharge column which, in turn, reduced the lasing efficiency, limited the useful diameter or cross section of the laser, and made it impossible to design high-power electrical CO_2 laser systems because saturation of the gain was relatively quickly reached. Typical laser output powers were of the order of 100 watts per meter of laser tube length. These problems were overcome by the use of convection or flow cooling of the laser gas. With flow cooling, arbitrarily large laser cross sections can effectively be used and arbitrarily high powers obtained. The specific heat of the laser gases in these devices is so high that even if the gas is dumped after use, up to 50,000 joules of laser power can be obtained per pound of gas flow. In 1969, Philco-Ford Corporation built a 6 kw, 4-inch-diameter by 2-meter-long, convection cooled CO_2 oscillator on contract under the ONR/ARPA laser program.

Simultaneously with the development of the convective flow system at Philco-Ford, other workers began exploring a convective mixing gas laser wherein nitrogen is electrically excited and subsequently flowed into the lasing chamber, where it is mixed with CO_2. Maintaining the desired discharge conditions in pure nitrogen is somewhat easier than producing such a discharge in a N_2-CO_2He mixture. This approach gives exceedingly high gains, but since only a fraction of the gas molecules can be excited, it results in a reduced maximum output energy per pound of flowing gas. United Aircraft obtained 11 kilowatts from a 1-meter-long mixing laser; however, problems encountered with efficiently transferring the excited nitrogen into the lasing chamber, difficulties in uniformly mixing the CO_2 with the excited nitrogen, and the substantial problems associated with separating the gases if closed cycle operation is desired, have caused abandonment of this approach and concentration on techniques whereby the electrical excitation occurs in the lasing chamber.

In the convectively cooled gas laser, the gas flow, the electrical discharge, and the laser action can all be oriented about independent orthogonal axes; however, the simplest geometry, and the first to be exploited by Philco-Ford and others, orientates all operations coaxially along a single axis and is essentially identical to the conventional conduction cooled CO_2 laser except that a high velocity gas flow is maintained. (Relatively high gas velocities of the order of sound speed, are required in this coaxial geometry in order to prevent overheating of the gas before it leaves the active region.)

This has introduced problems with doppler shifting of the gain profile; turbulence associated with the high velocity flows has on occasion induced instabilities in the gain; and, more serious, an upper limit to the length of the laser is established by how far the gas can flow before it gets hot. Other configurations, wherein

XUM

the gas flow is normal to the lasing direction, overcome many of these problems and are currently being exploited. Early experiments with electrical discharges transverse the flow direction encountered difficulty with the discharge being blown down stream. Placing the electric discharge in line with the direction of gas flow, but normal to the lasing direction, avoids the problem of "blowing out" the discharge, but this causes a lasing geometry which, except in a very large system, results in a short discharge path which can produce a relatively large loss in the cathode fall. Recently, "blowing out" the discharge when the field is normal to the flow direction has been overcome by the use of magnetic fields to confine the ionization contained in the discharge column to a relatively straight line and/or the use of RF excitation to provide an adequate degree of ionization on the up-stream edge of the discharge. These techniques will find application in smaller electrically excited gas lasers.

The major limitation to obtaining high-power electrical discharge laser systems has been the difficulty of developing electrode structures which are capable of producing multi-kilowatt glow discharges without streamering. The use of many small resistively ballasted electrodes is impractical for efficient high-power systems. United Aircraft Company, under a joint ARPA/Navy program, is developing large area, high-current electrodes which will permit the construction of multi-kilowatt, high-efficiency, CO_2 electrical systems.

In addition to the development of techniques for cooling the laser gas and building high-current glow discharge electrodes, there has been during the past year a considerable increase in understanding of the mechanisms by which electrical excitation of the vibrational states of nitrogen and CO_2 takes place. The Navy is currently sponsoring the study of electrical discharges at UAC. In this contract it has been shown that operation at the correct E/P (electric field strength to pressure) ratio can result in over 90 percent of the electrical energy loss being transferred to the lower vibrational states of N_2 and CO_2. This would result in an overall laser efficiency approaching 40 percent. In a normal laser discharge, the actual E/P that is developed is, among other things, determined by the degree of ionization required to maintain the current flow. At very low current densities, the E/P that naturally develops in a glow discharge is close to the optimum, and actual efficiencies as high as 32 percent (laser power out to electrical power in) have been observed, although under these circumstances the laser power densities are extremely low. Increasing the current density in order to bring the laser power density up to a few watts/cm^3 generally results in an increase in the E/P and a lowering of the overall laser efficiency to 10-15 percent. It has been recently recognized in work both at UAC and Avco that if the ionization is independently controlled, operation at the desired E/P can be maintained even at high current and laser power densities. UAC has experimented with the introduction of readily ionizable atoms such as Cs to provide the desired charge density.

Avco has used a double pulsing technique in which the electrodes are momentarily pulsed to a very high voltage which produces a uniform ionization throughout the gas. Then a constant voltage giving the desired E/P is applied. The relatively slow-moving, uniform positive ion background created throughout the gas volume by the high voltage pulse prevents streamering and reduces the electrode ballasting requirements, even when a large number of comparatively small electrodes are used. After a few milliseconds, the high voltage pulse is

XUM

again applied to renew and maintain the uniform ionization density. Using this technique, Avco has obtained outputs exceeding 20 kw at power densities of the order of 10 watts/cm^3 with an electrical efficiency approaching 30 percent. In other experiments, high-energy electron beams have been used as the source of ionization.

There is now every indication that high power CO_2 electrical discharge devices can be built with efficiencies of the order of 30 percent. The availability of a coherent light source with an efficiency comparable to presently available noncoherent illumination sources opens up a variety of military applications.

Wall-Less Proportional Counter for Tissue Microdosimetry Studies

Recent work by Dr. W. H. Ellett, Oregon State University, Corvallis, Oregon, on the detection of tissue cell damaging ionization in microscopic regions of the body has led to the construction of a wall-less proportional counter for microdosimetry studies. The development of the instrument was instigated by results obtained with a conventional counter which showed a greater difference in the rate of energy deposition between X-ray and cobalt irradiation. The difference was so large it was surmised that it might be due to perturbation in the measured event size spectra due to the wall of the proportional counter.

In order to measure the perturbation caused by the plastic wall of the spherical proportional counter a similarly shaped wall-less counter of approximately the same diameter was constructed. In this counter a spherical electric field is generated by a series of thin wire rings, of various diameters, concentric with a central stainless steel wire anode. The potential of each ring is adjusted so that a constant electric field, necessary for uniform gain, exists at the anode. Additional guard rings collect ions produced outside of the spherical volume. The arrangement of the apparatus allows the collecting volume to be mapped by means of coincidence events between the wall-less counter and a solid state detector. As far as is known, this is the first application of this kind of design to wall-less proportional counters.

Research Monograph Published

A definite monograph *Finite State Markovian Decision Processes*, by Cyrus Derman, has been published by the Academic Press. Professor Derman is a principal investigator in ONR's Reliability and Quality Control subprogram. His research at Columbia University is a major contribution to the theory of discrete dynamic programming. This monograph provides a rigorous systematic treatment of the optimal control of certain types of dynamic systems, such as those systems used for inventory or logistics systems. These systems are observed periodically, and after each observation the system is classified into one of a number of possible states; after each classification one of a possible number of decisions is implemented. The sequence of implemented decisions interacts with the chance environment to effect the evolution of the system. The mathematical abstraction of this process is called a Markovian decision process. Some applications which are comprehended by the mathematical structure are problems of (1) sequential search theory, (2) logistics replacement models, (3) material maintenance models and (4) computation of average outgoing quality level for continuous sampling plans. Such problems are of direct Navy concern.

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Research Notes

Optical Switches

The invention of "optical switches" that could play an important role in future communications systems and speed up computers was announced at the California Institute of Technology.

The crystal devices, only a few thousandths of an inch across, modulate and switch laser light on and off at speeds up to a billion times a second, much as transistors do for electric current. They operate in miniature integrated optical circuits that carry light instead of electricity in thin crystal films acting as wave guides.

The crystal modulators, as they are called, were invented by Dr. Amnon Yariv, Caltech professor of electrical engineering, working with Dr. Elsa Garmire, research fellow in applied science, and David Hall, a graduate student.

The devices, on which patent applications have been filed, are reported in the current issue of "Applied Physics Letters."

"There is much interest in the development of optical circuits in communications systems and also in computer design because such systems, in theory, are faster than electric, can handle more information through their multiplexing capabilities, and because they minimize unwanted feedback," Dr. Yariv explained.

"The bottleneck in the use of optical signals has been the large amount of electric power required to modulate them and the lack of efficient guiding systems," Dr. Yariv added. "This has made the system restrictive."

Constricting the laser beam into a guide with dimensions of a few microns makes possible a reduction of more than a thousandfold in electric power requirements as well as compact integrated circuits.

The optical switches took three years to develop. The work of the research team is supported by the Office of Naval Research and the Advanced Research Projects Agency. The unique crystals used in the research were grown by the United Aircraft Research Laboratories, East Hartford, Conn.

The switches developed by Dr. Yariv and his group are based on electrodes attached to wave guides. Voltages of less than 100 volts produced the modulation effects.

The wave guide—which plays a role similar to that of a wire in an electrical circuit—consists of a crystal on which has been grown (by heat and evaporation) a very thin (a few thousandths of an inch) layer of another crystal. The very thin layer will guide light—provided it has a greater ability to refract (bend) light than the substrate crystal layer. It must, in other words, have a higher refractive index.

In his work, Dr. Yariv has used gallium arsenide crystals in an impure form for the lower layer or substrate and in the purest form as the epitaxial or upper layer for the thin film.

Light from a laser is fed into this wave guide, which can carry the light around corners and for considerable distances in a miniature optical circuit with little loss of intensity.

So that the voltage may be applied to the crystal at one or more locations where switches are desired, a thin coat of metal is evaporated onto the top of the epitaxial layer and onto the bottom of the substrate. Wires are attached to both spots of metal.

Operation of the switch depends on the semi-conducting properties of the thin film, which makes it possible to impose an electric field on the wave guide, and the electro-optical effect, which enables one to control the optical properties of the wave guide by the electric field. This latter property is defined as the variation of the index of refraction which is proportional to the electric field.

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The electric field causes minute changes in the crystal's atomic arrangement which, in turn, induces a slight change in the refractive index (*i.e.*, the velocity of light).

This electric control of the index of refraction can be used in several ways for gating or modulating the light flowing through the wave guide.

Dr. Yariv's group demonstrated two different modes of operation. In one, the application of a voltage rotates the direction of polarization of the optical field. This effect can be used with polarizers to modulate the intensity of the guided light, the engineering scientist pointed out.

In the other mode, the application of an electric field to the wave guide has an effect which is equivalent to changing the physical height of the wave guide, thereby controlling the amount of light propagating through it, he added.

Some of the applications envisaged for the new optical circuit element include:

1. Putting many channels of information on optical carriers to transmit information.
2. Compact optical circuits for information processing.
3. Electrically controlled optical scanners and lenses for maneuvering the direction and amount of spread of optical beams.

Bubble Detection with the Doppler Ultrasonic Flowmeter

Navy decompression tables are based on empirical observations of actual dives and on calculations related to average gas solubilities and tissue perfusion/diffusion rates. But because of the variability in physiological make-up from person to person, some divers will develop symptoms of decompression sickness in spite of the proper use of the tables. Research is being conducted by ONR to assess the ability of a new instrument, the Doppler Ultrasonic Flowmeter (DUF) to detect gaseous emboli which may form during decompression before such emboli induce symptoms of decompression sickness. The DUF, consisting of cuff-like sensors placed around blood vessels, is designed to detect changes in sound frequency caused by bubbles acting on blood flow velocity. Dr. Kent Smith of the Virginia Mason Research Institute, Seattle, Washington, has implanted Doppler sensors around the pulmonary (lung) arteries, the anterior and posterior vena cavae (veins coming directly off the heart) and femoral (leg) veins of sheep. The sheep are then compressed and decompressed at a rate resulting in clinical manifestations of decompression sickness while using the DUF to monitor bubble formation. In all animals, Doppler changes were observed prior to the onset of decompression sickness, generally just in the anterior vena cava, then in the pulmonary artery. The Doppler signals continued to be present 24 hours after the animal was decompressed. The use of the DUF may prove to be a valuable contribution to the safety of naval divers.

Body Stress Responses to Low Oxygen

The human body responds nonspecifically to a number of stresses such as cold, fear, low oxygen and heat, by secreting hormones into the bloodstream which mobilize energy to provide for a higher level of activity to meet the crisis. The organs that secret these hormones are the adrenal glands, located atop the kidneys. An ONR contractor, Dr. S. F. Marotta of the University of Illinois is conducting research to trace the complex pathway of activation of the adrenal glands by low oxygen (hypoxia). It is important to understand this pathway so that its protective effects might be maximized and harmful over-reactions minimized in naval personnel exposed to low oxygen.

XUM

Low blood oxygen is sensed by two sets of specialized neural receptors in the neck/thorax region called the carotid and aortic chemoreceptors. Dr. Marotta has ascertained that, in response to hypoxia, these bodies send impulses up their connecting nerves to a lower brainstem center called the pons. The pons in turn activates a nearby region, the hypothalamus, which activates the adenohypophysis. The adenohypophysis then secrets a hormone which travels through the blood stream down to the adrenal cortex and stimulates the release of glucocorticoids, hormones which increase sugar, fat, and protein in the blood. The part of the pathway from hypothalamus to adenohypophysis to adrenal cortex has long been known, but the path from the chemoreceptors to the pons to the hypothalamus is newly being described in Dr. Marotta's work. In simplified form, his experiments consist of exposing anesthetized dogs to low oxygen and measuring the output (*via* adrenal vein) of adrenal hormones when different portions of the hypothesized part of the pathway are blocked. If there is no output of hormone, he then knows that what he has blocked is part of the activation pathway. Despite the complicated tangle of nerves involved he has discovered by this method that the stimulation to the pons is neural rather than chemical or hormonal and that the path from the pons to the hypothalamus is hormonal as well as neural.

New Optical Technique Aids NRL Scientists in Stress Analysis Experiments

The Naval Research Laboratory has announced a significant advance to aid in the interpretation of stresses in structures by the use of a newly developed computer technique for stress analysis research.

Mr. Robert J. Sanford, a research engineer who heads the Stress Analysis Section of the Ocean Technology Division, has found a new way to simulate complex stress-optic patterns of actual photoelastic models by use of the computer and an analytic definition of the pattern.

Mr. Sanford said that patterns obtained by the new technique pictorially represent the stress inside structures of any homogenous material; this information enables scientists or engineers to predict the life of the structure under service conditions.

This technique differs from previous ones in that the computer-controlled picture not only locates the position of the particular stress levels but also reproduces stress changes by tonal variations as they would be observed in photoelastic pictures from an actual experiment. Thus this technique generates patterns which are the visual equivalent of stress patterns from an experiment. The technique can be applied to simulate any type of polarized light experiment for which the light intensity relation is known, including the newly developed holographic interference method of stress analysis.

The Navy is continually seeking methods of determining the causes of structural failures under stress and ways of predicting such failures. Mr. Sanford's new approach in stress pattern investigations provides a valuable new research technique with which to investigate these failures; the end result will be better structures for Navy applications.

In this new mode of picturing analytic stress patterns, the enterprising young scientist employs a small real-time computer interfaced with a digital-to-analog converter which, in turn, controls the picture on an oscilloscope tube. The computer calculates the resultant light intensity at a chosen point based on the stress at that point and the assumed optical constants. This result is then converted to an analog voltage which modulates the intensity of the oscilloscope beam. Similarly, the coordinates of the point are converted to analog voltages which locate the point on the tube. This process is repeated until the desired density of points is achieved resulting in the image of a simulated stress pattern. A typical pattern contains over 100,000 such points.

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On the Naval Research Reserve

18th Annual West Coast Research Reserve Seminar

The Annual West Coast Research Reserve Seminar was recently held at the Fleet Anti-Submarine Warfare School in San Diego, California. Naval Reserve Research Company 11-5 sponsored the Seminar drawing talent largely from Naval Laboratories and defense industry in Southern California. The Seminar provided a balanced overview of technology, applications and operational requirements in the area of remote sensing.

The keynote address was delivered by the Chief of Naval Research, RADM C. O. Holmquist, USN, who emphasized the changing nature of fiscal priorities and the declining size of the research dollar. In a candid and forceful discussion the reservists were given a clear picture of what lies ahead; the need for spending research resources where the Navy will derive the most benefit, both in applications and in support for the Navy's programs was emphasized.

The new Special Assistant for Research Reserve, ONR Washington, CAPT Ross A. Hill, USNR, discussed the future of the Research Reserve Program including the effect of reduced mobilization billet assignments and the increasing emphasis on contributory projects by Research Reservists.

Topics discussed during the first week were sonar and ASW remote sensing, low-sight electro-optical systems including night vision equipment, and laser techniques. The second week started with a field trip to the Naval Acoustic Sensing Facility at Pt. Loma which was followed by a program at the Fleet-Anti-Air-Warfare Training Center. The seminar staff which was headed by CAPT B. H. Gardner, USNR and CDR W. E. Selph, USNR are to be commended for a job well done.

NRRC 5-10

Members of Naval Reserve Research Company 5-10, Bethesda, Maryland, recently honored four retiring members: CDR Frank D. Hansing, CDR Maynard Eicher, CDR James B. Eades, Jr., and LCDR Joseph H. Graham. Commanders Hansing and Eicher were formerly Commanding Officers of the company.

CDR Eicher, who is employed at the Naval Medical Research Institute, has the distinction of being a "plank owner" with NRRC 5-10, joining the company when it was formed in 1950. The twentieth anniversary of the company was celebrated at its annual dinner meeting in late May.

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Seventeen officers of Naval Reserve Research Company 5-10 completed an intensive two day orientation at the White Sands Missile Range and the Army Air Defense School, Ft. Bliss, Texas. The visitors were fortunate in having their visit coincide with a scheduled test firing of a standard surface to air missile.

On Saturday members of the staff of the U.S. Army Air Defense School presented a series of briefings on various Army missiles and weapons systems, including the Nike series. To conclude the training a tour was made of the MacGreggor Range which is used during the training of air defense forces.

NRRC 9-1

Naval Reserve Research Company 9-1, Chicago, Illinois, sponsored a three-day weekend seminar entitled "Crisis in Environment." The Seminar focused on several aspects of pollution with presentations made by members of Northwestern University's Students for a Better Environment.

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IN THIS ISSUE

VOL. XXIII, NO. 10

How Gas Atmospheres Produce Failure in Metals ..... M. R. ACHTER 1

The Naval Research Laboratory has completed a study on the effect of gaseous atmospheres on mechanical properties of metals, especially at high temperature. The rate of crack growth can be related quantitatively to the pressure of gas in the atmosphere.

Statistical Randomness and 1/f Noise ..... JAMES J. BROPHY 8

Noise is the signal produced by thermal agitation or by flow of charge in solids. Satisfactory operation and high sensitivity of infrared detectors, transistors, amplifiers, and other solid state devices vital to naval communications and detection systems depend on understanding and controlling this noise.

History of Electrically Excited CO_2 Lasers ..... F. W. QUELLE 22

Research Notes 25

On the Naval Research Reserve 28

Computer-generated holographic interference pattern of stresses in a disk under diametral compression as obtained through a new technique at the Naval Research Laboratory. This technique can be used to simulate any type of stress-optic experiment for which the light intensity can be expressed as a function of the stress. This technique differs from previous ones in that the tonal variations of the experimental pattern are reproduced and thus the simulated pattern is a reconstruction of a stress optic experiment. *See page 27.*

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